Exergetic optimisation of a solar energy installation

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Abstract: This paper deals with the Exergetic optimisation stutdy of the PCM's slabs- Solar Energy Storage Tank (SEST). Both melting temperature and the maximum power output taking into account the phase change process are determined.

Key words: Exergy, Optimisation, Solar energy, Phase change material.

Introduction

One of the key for Solar Energy success resides without any doubt, in an effective thermal storage. Among solar thermal energy storage techniques, we mention:

- The thermally stratified storage (sensible heat), which is an effective technique, that's widely used in energy conservation and load management applications. Analytical, experimental, and numerical studies have been carried out on its performance [1-3].
- Reversible chemical heat storage which is based on the conversion of solar radiation into-high temperature heat. It consists of a closed loop [4-6] or open-loop [7] system of reactants passing to endothermic "Solar energy storage" and exothermic "solar energy recovery" reactors.
- Latent heat thermal energy storage. Solar energy is stored in phase change material (PCM). The main features of PCM are their high-energy storage density and their ability to give up the stored energy at a constant temperature. These characteristics motivate for their applications. The most analysed latent heat energy storage unit is the shell and tube one, with the PCM filling the shell and the heat transfer fluid flowing through the tubes [8]. A detailed discussion on the solar energy storage using PCM can be found in [9]. The installation was treated as a transient –continue system using finite difference. The analysis of PCM melting process, which falls into the moving boundaries problems, was performed using the enthalpy formulation. The PCM slabs were considered to be bathed in two different fluids.

Several methodologies for Thermal Energy Storage (TES) evaluation and comparison have been investigated [10,11] concluding that the only adequate method providing illuminating information is that based on the Second Law of Thermodynamics, that's, availability analysis. In fact, energy efficiency which is the ratio of the energy returned from the storage to the energy originally delivered to the storage, does not take into account all the considerations necessary in Thermal energy storage evaluation as could be storage duration, and the temperatures of the supplied and recovered thermal energy and the surroundings. Availability analysis yields efficiencies which provide a true measure of how nearly actual performance approaches the ideal, and identifies more clearly than energy analysis the causes and locations of thermodynamics losses. Consequently, the availability analysis can assist in improving and optimising TES designs.

The purpose of this article is the presentation of a most general exergetic optimisation of the PCM's slabs- solar energy storage tank (hereafter SEST), Fig. 1, and to determine both optimal melting temperature and the maximum power output taking into account the phase change process.

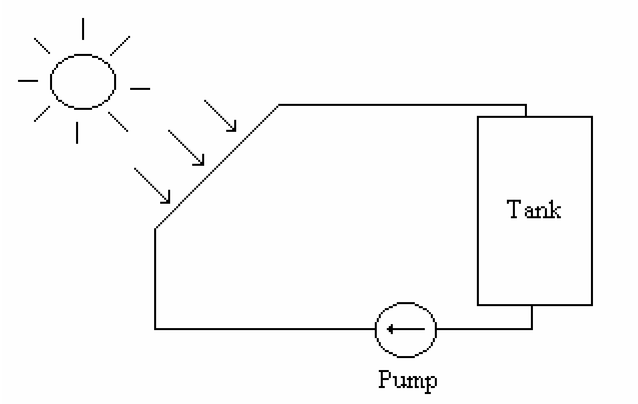

Fig. 1 Solar Installation

2. Availability maximisation of SEST with PCM

Once the hot stream of a flow rate m at temperature T_{in} comes in contact with a PCM, a fractional energy of the hot stream is released to a PCM and consequently hot stream's temperature falls to T_{out}. Assuming both steady state and PCM at the melting temperature (saturated solid state), T_m, it could be deduced therefore that;

$$T_{out} = T_m + (T_{in} - T_m)e^{-N_{tu}} \qquad (1)$$

where $N_{tu} = \dfrac{UA}{m_w Cp_w}$, A is the heat transfer area between the hot stream and PCM and U is the overall heat transfer coefficient based on A. Considering that SEST with PCM performs like a heat engine using Carnot cycle, that's, heat leaves the high temperature reservoir at temperature T_m and goes into the heat engine. The heat engine does work, W, and reject heat into the low temperature reservoir at temperature T_L. Then

$$\frac{W}{m_w Cp_w (T_{in} - T_{out})} = 1 - \frac{T_L}{T_m} \qquad (2)$$

and after combining with Eq. (1), it yields

$$W = m_w Cp_w (T_{in} - T_m)(1 - e^{-N_{tu}})(1 - \frac{T_L}{T_m}) \qquad (3)$$

$T_{m,opt}$ maximising Eq. (3) is

$$T_{m,opt} = (T_{in} T_L)^{\frac{1}{2}} \qquad (4)$$

This result coincide with the optimal latent heat storage temperature proposed by *Lim et al.* [12], however the expression of the maximum power output deduced by *Lim et al*. does not reflect the phase change process as the following equation obtained after substituting Eq. (4) in Eq. (3)

$$W = m_w Cp_w T_{in} (1 - e^{-N_{tu}})[\ 1 - (\frac{T_L}{T_{in}})^{\frac{1}{2}}\ ]^2 \qquad (5)$$

3. Case study

A complete solar installation situated at Lleida city in Catalunya, Spain, is studied. For all calculations of parameter's design and optimisation, we consider a March's representative day, that's, date 16. Tubing thermal losses between SC and SEST with PCM are neglected. The N_{tu} is of a great usefulness and significance. In fact, it gives precious information for design as if number of slabs should be changed or not. The fractional energy, Ψ, given up by the melted PCM of a melting temperature, T_m, and recovered by the entering water is defined as the actual energy given by the PCM in time t divided by the total energy, That's, $\Psi = \frac{T_{mean} - T_m}{T_{in} - T_m}$. The water's mean temperature bathing each PCM's hourly section is evaluated simply by $T_{mean} = \frac{T_{out} + T_{in}}{2}$. The other important key design in this problem is the melted thickness, $\delta(t)$, which is, function of a PCM thermal properties, thickness and boundary conditions, that's, h and T_{mean}. Fig 2 shows the variation of the PCM's optimal melting temperature, $T_{m,opt}$ and the water's mean temperature bathing the PCM's slabs, T_{mean}, with the PCM's slabs height during the first six hours, i.e.; $9hr$ to $15hr$. As the PCM's slab's height increase, $T_{m,opt}$ and T_{mean} decrease. Thus, for $l = 0.135m$, $T_{m,opt}$ *=363ºK* and T_{mean} *=365ºK* when for $l = 0.38m$, $T_{m,opt}$ *=327ºK* and T_{mean} *=332ºK.* From $15hr$ to $18hr$ and depending on the chosen PCM's melting temperature, a fractional energy, Ψ, will be given up by the melted PCM to the entering water. Fig 3, shows that for $l = 0{,}135m$, Ψ is of about *58,54%* and for $l = 0{,}38m$, Ψ is of *25,49%.* Considering RT-PCM products and from Fig.4, for $T_{m,opt}$ *=327ºK*, the recovered energy by the entering water is of *612,18 kJ* when the energy to be recovered is of *1836,54 kJ*. However, for $T_{m,opt}$ *=363ºK,* the recovered energy by the entering water is of *561 kJ* and the energy to be recovered is *406kJ*. Thus, the energy quality to be delivered at $T_{m,opt}$ *=363ºK* is 5 times better than the energy to be delivered at $T_{m,opt}$ *=327ºK.*

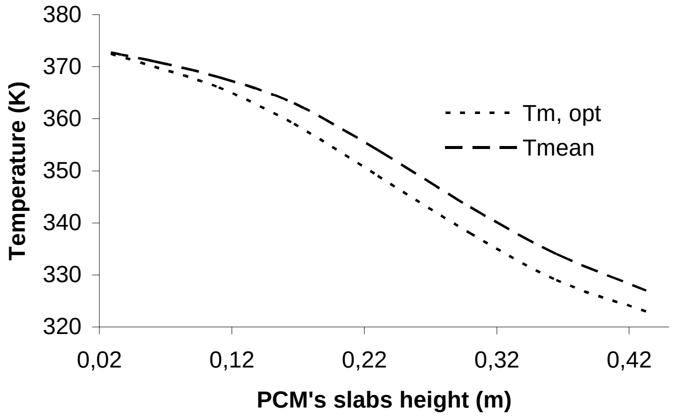

Fig. 2 Variation of PCM's optimal melting temperature and water's mean temperature bathing PCM's slabs with the PCM's slabs height

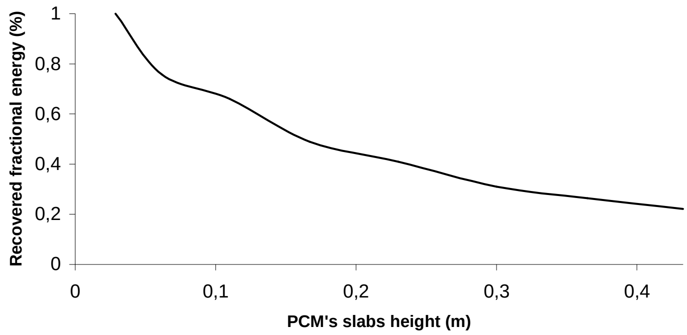

Fig. 3 Variation of the recovered fractional energy as a function of PCM's slabs height

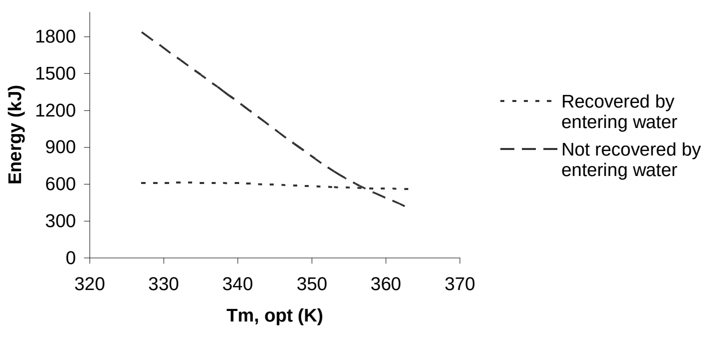

Fig. 4 Variation of recovered and not recovered energy with the chosen PCM's optimal temperature

4. Conclusion

A most general exergetic optimisation of the whole solar energy installation has been carried out for March representative day at Lleida Spanish city. As a result, the exergetic optimisation study of the PCM's slabs-SEST gives optimal melting temperature. Results show that T_m ranges between *327ºK* and *363ºK*. For each melting temperature corresponds its PCM's slabs height. Thus, for $T_m=327K$, $l=0,38\ m$ when for $T_m=363K$, $l=0,135\ m$. The fractional energy, Ψ, function of T_m, given up by the PCM's slabs to the entering water has been also examined. As a result, for $T_m=363K$, $\Psi=58,54\%$ and for $T_m= 327K$, $\Psi=25,49\%$. Therefore, the energy to be recovered at $T_m=363K$ is five times better in point of view of quality.

References

[1] H. Yoo, C-J. Kim and C. W. Kim, 1998, Approximate analytical solutions for stratified thermal storage under variable inlet temperature, Solar Energy, Vol. 66, No. 1, pp. 47-56

[2] J. E. B. Nelson, A. R. Balakrishnan and S. Srinivasa Murthy., 1999, Experiments on stratified chilled-water tanks. Int. J. Refrigeration. 22, pp. 216-234.

[3] J. E. B.Nelson, A. R. Balakrishnan and S. Srinivasa Murthy, 1999, Parametric studies on thermally studied chilled water storage systems. Applied thermal Eng. 19, pp. 89-115

[4] K. Lovegrove, A. Luzzi and H. Kreetz , 1999, A solar driven ammonia-based thermochemical energy storage system. Solar Energy, Vol. 67, Nos. 4-6, pp.309-316

[5] H. Kreetz and K. Lovegrove, 1999, Theoretical analysis and experimental results of a 1 kW_{chem} ammonia synthesis reactor for a solar thermochemical energy storage system. Solar Energy, Vol. 67, Nos. 4-6, pp.287-296

[6] K. Lovegrove, A. Luzzi, M. Mccann and O. Freitag , 1999, Exergy analysis of ammonia-based solar thermochemical power systems. Solar Energy, Vol. 66, No. 2, pp.103-115

[7] F. Aghbalou, A. Touzani, M. Mada, M. Charia and A. Bernatchou, 1998, A parabolic solar collector heat pipe heat exchanger reactor assembly for cyclohexane's dehydrogenation: A simulation study. Renewable energy, Vol. 14, Nos. 1-4, pp.61-67

[8] M. Esen, A. Durmus, A. Durmus, 1998, Geometric design of solar-aided latent heat store depending on various parameters and phase change materials. Solar Energy, Vol. 62, No. 1, pp. 12-28

[9] F. Aghbalou, F. Badia and J. Illa, 2002, Design and analysis of a thermal solar energy storage using PCM, FIER 2002 Proceeding, Vol. 2, pp. 395-401

[10] M.A. Rosen and I. Dincer, 2003, Exergy methods for assessing and comparing thermal storage systems, Energy research, 27, pp. 415-430

[11] I. Dincer, 1999, Evaluation and selection of energy storage systems for solar thermal applications. Energy research , 23, pp. 1017-1028

[12] J.S. Lim, A. Bejan and J.H Kim, 1992, Thermodynamics optimisation of phase change energy storage using two or more materials. Energy resources Technology, 114, pp. 84-90